FERMILAB-CONF-89-285-AD

COMPENSATION OF TIME VARYING FIELDS IN THE TEVATRON SUPERCONDUCTING MAGNETS

D. E. Johnson and D. A. Herrup
*Fermi National Accelerator Laboratory**

Abstract

While the Tevatron is stored at 150 Gev for injection of protons and pbars during a Colliding Beam cycle, the sextupole fields in the Tevatron dipoles decay in a predictable manner. This decay has been further measured and compared with the behavior predicted by the theory of flux creep[1] in the superconducting filaments of the magnet cable. A correction algorithm has been implemented which automatically adjusts the current output of function generators for the two orthogonal sextupole correction circuits. Results of the implementation are presented.

Introduction

When the Tevatron was converted from a fixed target accelerator with injection porches of a few seconds to a collider with injection porches of many hours the chromaticity of the accelerator was observed to change as a function of time at the 150 Gev injection porch.[2,3] The horizontal and vertical chromaticities changed in opposite directions which is consistent with a time varying sextupole moment, b_2, of the machine. Subsequently, it was found that this time variation is due to the time dependent sextupole moment of the superconducting dipoles. [3] The expression for the chromaticity of the accelerator at a constant energy, with correction sextupoles, is given by

$$\xi_{x,y} = \xi_{x,y}^{nat} \pm < \eta\beta_{x,y} b_2(t) > \pm S_{x,y}(t) \quad (1)$$

where $\xi_{x,y}^{nat}$ is the natural chromaticity of the machine (for the Tevatron, -22.5), the term in brackets is the contribution due to the b_2 component of the dipoles, and $S_{x,y}$ are the sextupole contribution in two orthogonal sextupole circuits.[4] The energy dependence of b_2 is contained in the standard excitation hysteresis curve followed during ramping. If the excitation current is held constant at a low field, i.e. 150 Gev injection porch, the time dependent b_2 becomes non-negligible and must be controlled. Figure 1 shows a typical hysteresis curve for a 1 meter Tevatron dipole coil.[5]

These early observations of the time dependent nature of the sextupole moment in superconducting dipoles stimulated detailed laboratory measurements of the de-magnetization effects of the superconducting cable [6] and persistent current measurements on short sample dipole coils and Tevatron magnets. [5,7] The observations in each of these studies show a time variation in the magnetic field which can be described by a $ln(t)$ behavior indicative of flux creep.

Early Tevatron Measurements

Measurements of the time dependent chromaticity change have been reported by Finley, et. al.[3]. They report variations in the initial tunes and chromaticities which were dependent on the details of the recent history of the machine (e.g. whether the ramp had been turned off completely or how many ramps to flattop had been performed before setting at 150 Gev). To reduce the observed ramp history effect, a policy of starting each 150 Gev injection porch for Collider operation with a series of 6 ramps was adopted. The effect of ramp history has also been observed in studies on a single Tevatron dipole by Hanft et. al.[7].

*Operated by the Universities Research Association under contract with the U. S. Department of Energy

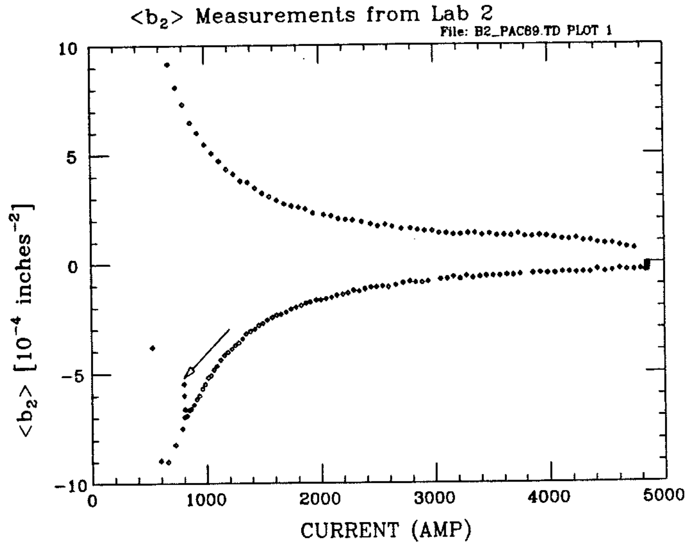

Figure 1: Typical b_2 hysteresis curve for a 1 meter Tevatron style dipole coil (Ref. 5). The arrow indicates the b_2 drift at a constant excitation.

They[3] further observed chromaticity changes on the order of 60 units when the time dependent b_2 was uncompensated. Their measurements of the uncorrected chromaticity change during the injection front porch were made by adjusting the correction sextupole circuits to obtain zero chromaticity. This condition of zero chromaticity is easily observed on a spectrum analyzer connected to Schottky detector[8]. The b_2 was inferred from the chromaticity settings (e.g. currents in the two orthogonal sextupole loops) required to produce zero chromaticity in the machine.

We plot the b_2 data from these measurements on a logarithmic time scale. They show a linear dependence on the $ln(t)$. The data were fit to the function

$$b_2 = A + B\ ln(t). \quad (2)$$

The constants A and B were found to be -2.3646 and .263, respectively. The data (open squares) and the resultant fit are shown in Figure 2. The data point at .36 seconds was taken on a short injection porch during a 512 Gev fixed target ramp. The remainder of the data (open squares) were measured immediately following 6 ramps to 900 Gev after being stored at 900 Gev for some hours. The first of these data points was measured within 5 minutes after the Tevatron energy was set to the 150 Gev injection level with measurements being taken every few minutes for the next several hours. The additional data displayed in figure 2 are displaced but consistent with the $ln(t)$ decay.

Operational Implementation

The fit to the above data, shown in fig. 2 was encoded into the Colliding Beams Sequencer[9] and is used to calculate a corrected value of b_2 dependent on the length of time at 150 Gev. This calculated value of b_2 is then used by another program[4] to adjust the currents in the

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

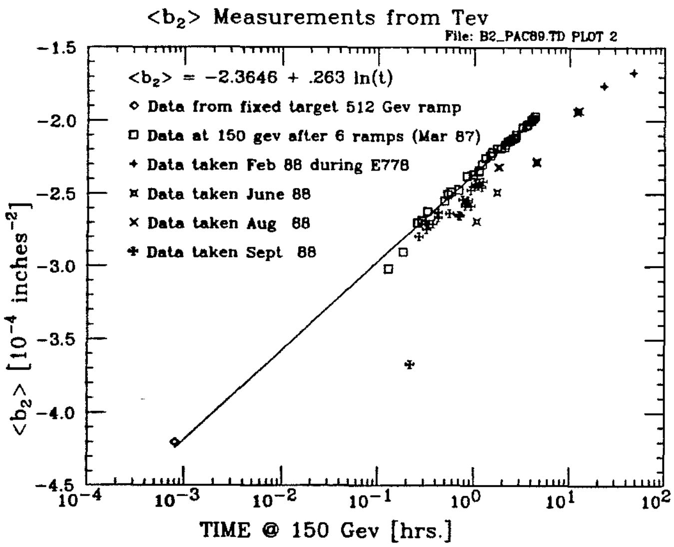

Figure 2: Measurements of the time dependent b_2 field of the Tevatron taken at various times. The data span 5 orders of magnitude in time. The solid curve is a fit to the data taken March 1987 (eqn. 2).

sextupole circuits to compensate for the time dependent drift in the b_2 component of the superconducting dipoles while at 150 Gev. This automatic adjustment is supervised by the Periodic Scheduler feature of the CBS. The frequency of this compensation may be adjusted from 1 minute to 2 hours, but typical values tend to be in the range of 2 to 10 minutes, depending on how long the Tevatron has been at 150 Gev.

During the early part of the Collider run the tunes and chromaticities were routinely adjusted during shot setup to obtain the desired chromaticities on the order of 2-5 units as seen by the synchrotron sidebands on the tune spectra. If the horizontal chromaticity was adjusted too close to zero too and early in the set up procedure, either the 'head-tail' instability would cause beam loss or beam loss during the injection process would be observed. About midway through the Collider run an effort to reduce the manual tune and chromaticity adjustments and speed the shot set up procedure was undertaken. Data was accumulated on the final values for the tune and chromaticity settings. Two sets of values, associated with different ramp histories of the Tevatron prior to the six ramps, for the chromaticity settings occurred frequently.[10] These were adopted as the initial values for the chromaticity settings at the 150 Gev injection porch. When ramp history indicated that the Tevatron had been off or at 150 Gev prior to the six ramps, Cx would by increased 4 units and Cy would be decreased by 3 units.

Test of Algorithm

The algorithm used to track the time dependent b_2 was tested by letting only the algorithm change the currents in the sextupole circuits and measuring the chromaticity for two hours after setting at 150 Gev. Since the Tevatron had been at 150 Gev for several hours prior to the measurement, it was ramped to 900 Gev 6 times and returned to the 150 Gev level to follow the standard procedure used during the Collider run.

The chromaticity measurements were made by varying the RF frequency and recording the corresponding changes in tune. The RF frequency was changed by $\pm$ 91 hz corresponding to a $\pm$ 1.72 mm change in radial position. The tunes were split by about .02 (i.e. ν_x =.423 and ν_y = .405) to avoid any confusion due to coupling, especially with large chromaticity. The chromaticity is given by

$$\xi_{x,y} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right) f_{rf} \, \frac{\Delta \nu_{x,y}}{\Delta f_{rf}} \qquad (3)$$

where, for 150 Gev, γ is 160.915, γ_t is 18.75 and f_{rf} is 53.103688 Mhz. A linear least squares fit to the three tune and Δf_{rf} values was performed to calculate the chromaticity. The results of these measurements are shown in Figure 3.

The uncertainty in the data with large chromaticity is due to the inability to determine the central tune line. The errors are quantized in terms of synchrotron sidebands. For a f_s of 80 Hz. and a f_{rev} of 47713.15 Hz. the sidebands are separated by .0017 tune units. If the same sideband was not measured for each of the three RF frequencies, an error of 1.4 units in chromaticity would be introduce for each sideband in error. The accuracy in measuring the peak of a sideband in on the order of .4 units of chromaticity. These uncertainties are reflected in the data shown in fig. 3 and 4.

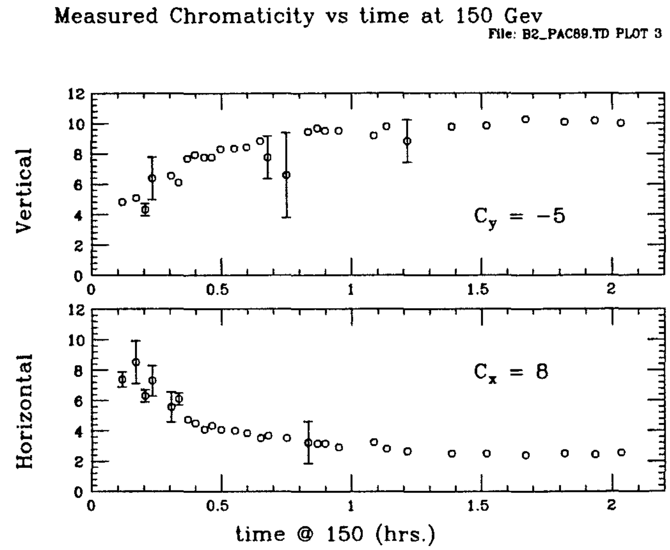

Figure 3: Measured chromaticity as a function of time at 150 Gev to test the b_2 tracking algorithm; b_2 = -2.3646 + .263 $ln(t)$.

Since the chromaticity settings were held constant, any change in measured chromaticity is due only to the difference between the b_2 of the magnets and the calculated b_2 used to adjust the current in the correction circuits.

These data show an approximately equal and opposite $d\xi/dt$ for horizontal and vertical chromaticities. The chromaticity changes by about 4 units during the first half hour and 2 units during the next half hour. The data between hour 1 and 2 show little change in chromaticity. This change in chromaticity is down by an order of magnitude over the uncorrected data reported by Finley et. al.[3] used to construct the compensation algorithm.

In a similar manner to the data taken in March '87, the average b_2 of the Tevatron was inferred from the chromaticity measurements. This data and a fit to the function in equation 2 (solid line) are shown in Figure 3 along with the the fit to the 1987 data [3]. Comparison between the two data sets show that the initial value of b_2 in the recent data set is larger and the decay rate (slope) is smaller than that of the 1987 data. The .2 unit offset in b_2 corresponds to approximately 6 units of chromaticity seen in figure 2.

The differences seen here led us to permanently include a chromaticity measurement at 150 Gev in the operational filling procedure, prior to injecting pbars. A software program [11] was implemented which would automatically vary the Tevatron RF, store the associated tune spectra (as read from the spectrum analyzer), and record the current settings of the tune and sextupole circuits, and the time at 150 Gev for later analysis.

Operational Data

Figure 5 shows data taken over a 5 week period in February and March of this year. As this data was taken in an operational mode (vs a dedicated study), the ramp history prior to the 6 ramps varied from the Tevatron being stored at 900 Gev between 1/2 to 36 hours to being off

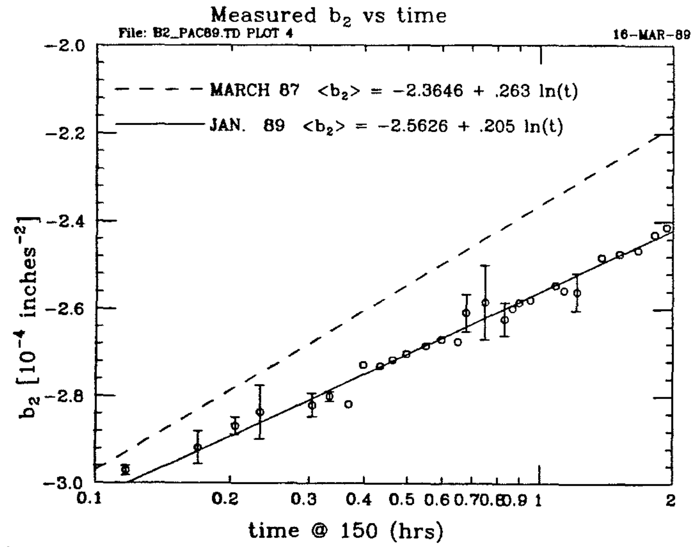

Figure 4: The data points represent the measured b_2 component of the Tevatron as a function of time at 150 Gev. The solid curve is a fit to the data using equation 2 (i.e. b_2 = -2.5625 + .205 ln(t). The tracking algorithm is shown as the dashed curve

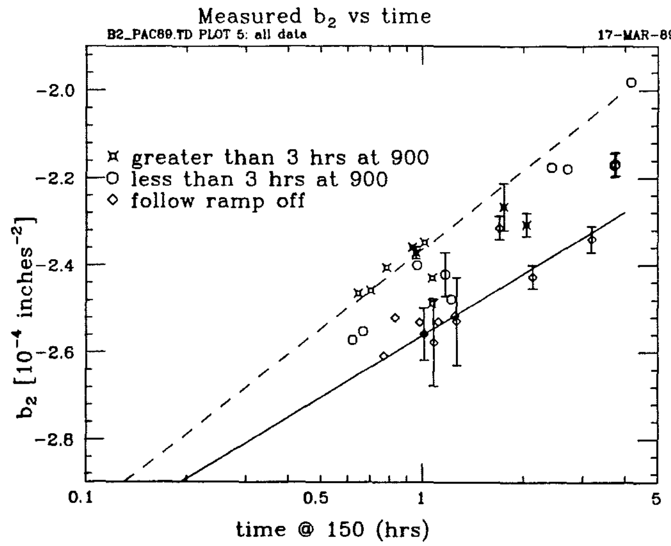

Figure 5: Measured average b_2 of the Tevatron during routine shot set up over a five week period. Most of the data was taken when the Tevatron was at 150 Gev between 1/2 and 2 hours. The dashed and solid curve is the fit to the data taken March '87 and January '89, respectively.

just prior to the 6 ramps. A cut was performed on the data according to the ramp history prior to the 6 ramps. The three most often encountered histories prior to the six ramps were: following normal pbar-p stores of many hour durations, following a quench or access in which the Tevatron was turned off, or following short proton only store (under a few hours). The detailed ramp history of each of the stores show additional scenarios that have not been differentiated in this cut; for example, several data sets were ramped longer than the required 6 times. The data falls between the two curves. The majority of the ramp off data follows the lower curve while the data gathered following the end of a normal store tends toward the upper curve. Studies on a single Tevatron dipole magnet by Hanft, et.al. [7] report a change in the initial sextupole field when the flattop duration of a single ramp was varied. The longer duration flattop resulted in a lower initial sextupole field and the subsequent decay deviated from being linear in $ln(t)$

Conclusions

We have presented the our current procedure for compensation of the time dependent b_2 component of the superconducting dipoles in the Tevatron. This has reduced the chromaticity drift while at 150 by an order of magnitude. We show data taken during regular Collider operations which show a chromaticity spread at 1 hour on the injection porch on the order of 6 units. This data is also suggestive of an effect due to the prior ramp history is still present.

Acknowledgement

We would like to thank D. Finley for his assistance in the taking the data shown in figures 3 and 4 and many helpful discussions.

References

1. P. W. Anderson, "Theory of Flux Creep in Hard Superconductors", Phys. Rev. Letters 9, p. 309, (1962).
2. R. P. Johnson, "Initial Operation of the Tevatron Collider" IEEE Proceedings of 1987 the Particle Accelerator Conference, Washington D.C., March 16-19, 1987, pp. 8-12.
3. D. A. Finley et. al., "Time Dependent Chromaticity Changes in the Tevatron", IEEE Proceedings of the 1987 Particle Accelerator Conference, Washington D.C., March 16-19, 1987, pp. 151-3.
4. R. W. Goodwin and R. P. Johnson, Proceedings of the 12^{th} Int. Conf. on High Energy Accelerators., Fermilab, Aug., 1983.
5. D. A. Herrup et. al., "Time Variations of Fields in Superconducting Magnets and Their Effects on Accelerators", presented at the 1988 Applied Superconductivity Conference, San Francisco, Ca., August 21-25, 1988.
6. M. Kuchnir A. V. and A. V. Tollestrup, "Flux Creep in a Tevatron Cable", presented at the 1988 Applied Superconductivity Conference, San Francisco, Ca., August 21-25, 1988.
7. R. W. Hanft et. al., "Studies of Time Dependence of Fields in Tevatron Superconducting Dipole Magnets", presented at the 1988 Applied Superconductivity Conference, San Francisco, Ca., August 21-25, 1988.
8. D. Martin et. al., "A Schottky Receiver for Non-Perturbative Tune Monitoring", paper T-9 presented at this conference
9. D. E. Johnson and R. P. Johnson, "The Colliding Beams Sequencer", paper U-24 presented at this conference.
10. B. Hanna, J. P. Morgan, private communication.
11. G. Jackson, applications program used for chromaticity measurement.